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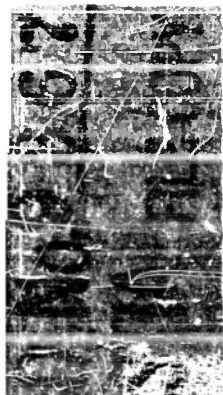
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A COMPARISON OF CERTAIN WIND,

TIDE GAUGE AND CURRENT DATA

By

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September 1952

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                                    Director

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A COMPARISON OF CERTAIN WIND, TIDE GAUGE AND CURRENT DATA

The collecting of continuous oceanographic data at sea has been hindered by the cost of maintaining scientific vessels to the extent that such data are available only for short periods in small areas. Oceanographers have long sought methods of obtaining running accounts of conditions at sea by means of data obtainable on shore. Tide gauge data and winds over the ocean have been suggested as indicators of the fluctuations in the Gulf Stream. Some of the studies already made are by Montgomery (1938), Iselin (1940), and Fuglister (1951). Two studies in progress are those by Stommel and Wertheim dealing with electrical potential across the Straits of Florida, and by the University of Miami on the Florida Current. It is hoped that these two studies will result in a greater understanding of the significance of tide gauge and wind data.

Meanwhile it is thought profitable to continue along the lines developed by Montgomery, Iselin, and Fuglister, but determining wind values from mean weather maps rather than from climatological records. The principle purpose of this paper is to compare winds with tide gauge readings in both long- and short-period averages. In view of theoretical implications, current and transport are important in the discussion.

Theory

Winds and currents. Many theories have been advanced to explain the circulation of water in the main gyral of the Gulf Stream System. Perhaps the most prominent of these is the "wind-driven" theory according to which the stress of the wind is what puts the water in motion. In a mathematical treatment Munk (1950) shows that a circulatory current system such as the Gulf Stream System responds to the curl of wind stress acting upon it. This suggests that a measure of the stress over the whole gyral, i.e., the stress exerted by both the westerlies and trades, will correspond to the flow of water in the System. Stommel (1951) uses wind stress over the entire gyral in explaining the narrow strong currents in the Gulf Stream. Not all of those in the "wind-driven" school believe that the westerlies are necessary to the calculations and there is indeed considerable evidence pointing to the trades alone as the prime mover.

Another school believes that both the water and wind circulations are the results of changes in insolation and radiation with latitude; i.e., that the two circulations are heat engines.

Under the "wind-driven" theory it seems likely that
fluctuations in the stress should result in corresponding
fluctuations in the flow. Under the "heat-engine" theory,
while the wind circulation is not responsible for the water
circulation, it is still possible that the two circulations
may undergo similar fluctuations in response to variations
in the heat balance.

Tide gauges and current. One form of the geostrophic
equation states that, for a given latitude and density con-
dition, the flow along the contours of an isobaric surface
is proportional to the slope of that surface at right angles
to the contours. In using the geostrophic equation one neg-
lects the effects of friction, curved contour lines and an
unsteady state. The variation of these effects is probably
small here since we are dealing with average fluctuations
and a large and fairly constant radius of curvature. To
transform sea level into an isobaric surface we must add a
correction for atmospheric pressure to our sea level heights.
This has been done to all the tide gauge data used here.

Application of Theory

Tide gauges. The tide gauge data used here are all from
stations near the western section of the current gyral where
the currents are strong, narrow, and better-known. A pair of
gauges on opposite edges of the Stream should give good repre-
sentative slopes. Not having such an ideally located pair of
gauges we must get our data from gauges less favorably placed.
The gauges at Bermuda and Charleston straddle the Stream,
although at some distance from it. Montgomery (1938) showed
that the Charleston gauge was representative of sea level in
the open ocean offshore and it is assumed that the other
gauges used are similarly representative. In view of his
correlation between onshore wind at Savannah and height of
sea level at Charleston, we must be aware of a possible simi-
lar effect at the other gauges. Miami and Cat Cay bracket
the Florida Current closely but the Cat Cay record is short
and both stations are to the left of the Antilles Current.
Figures for the Miami gauge will be shown later on the basis
of the Iselin (1940) statement that the major fluctuations in
sea level, accompanying changes in current, take place on the
left side of the current. Miami is very close to the edge of
the current. The Galveston gauge is much farther away from
the current yet it may respond to current fluctuations.

The tide gauge data were obtained from U. S. Coast and
Geodetic Survey records and from a very comprehensive compila-
tion of records gathered by Dr. Walter H. Munk of Scripps
Institution of Oceanography.

<u>Currents</u>. Because currents are the theoretical link between winds and tide gauges, some current figures are shown. The long-period averages are from surface current data of the Hydrographic Office (1946). These data are based on relatively few observations in certain areas and one must either confine his investigations to those areas in which there are many observations, as Fuglister did, or hope that the averaging of many one-degree squares will provide good statistical samples in those areas which have fewer observations per square.

The short-period data are the Gulf Stream transport figures given by Iselin (1940). They consist of thirteen values from the period May 1937 to February 1940. Iselin carefully selected the hydrographic stations used for the calculations so as to get, as far as possible, the transport of the Stream proper, and to exclude any transport in waters adjacent to the Stream.

<u>Winds</u>. Many wind rose and resultant wind charts of the North Atlantic are available for the study of long-time averages, but such charts rarely, if ever, show series of short-period averages. The wind data used here were obtained by measuring the U.S.W.B. (1946) Normal Pressure Maps (long-time averages) and the U.S.W.B. (1943) Monthly Mean Pressure Maps (short-time averages), with a geostrophic template.

For the construction of the template, the geostrophic equation was put in the form:

$$V = K \frac{\Delta P}{C} \quad \text{where:}$$

V = geostrophic wind velocity (component)
$K = \rho 2 \omega$ (a constant)
ΔP = pressure difference
$C (= \sin \phi \, \Delta X)$ is a constant
ϕ = latitude
ΔX = distance over which ΔP is measured

C is kept constant by varying ΔX in inverse proportion to the sines of the latitudes where the measurements are made. Thus, V is proportional to ΔP whatever the latitude, and the values from the various measuring points of the template can be averaged with the same weight. The wind values shown have been left in terms of ΔP (mb.). No allowance has been made for curvature of isobars (i.e., the gradient wind has not been figured). We cannot determine stress from these wind values since we do not know the distribution of the various wind forces which make up the averages, or the exact ratio between geostrophic wind and surface wind. It
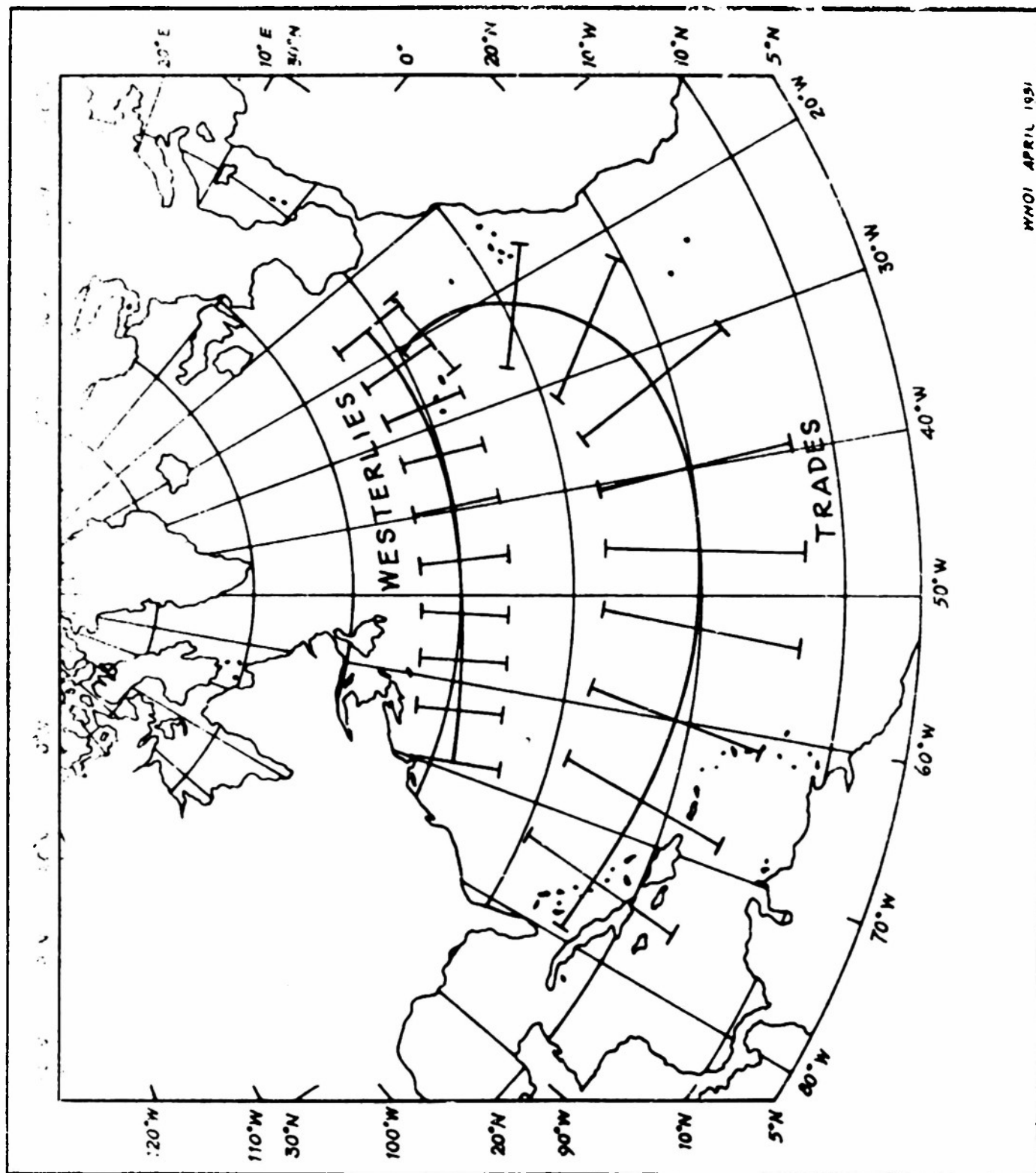
is assumed, however, that in averages over periods of a
month or more, that the geostrophic wind is, to a close
approximation, proportional to the stress.

In studies such as this where one wishes to compare
wind values with other data, it is difficult to chose the
exact area in which to measure the wind field. The inves-
tigator is confronted with the decision as to whether any
area he has chosen for measurement adequately encompasses
the "effective" field and yet, at the same time, excludes
areas, of no significance to the study, which may not have
the same fluctuations as the "effective" area.

In making the template, it was much easier to choose
a measuring area in the more homogeneous trades than in the
more variable westerlies. The Northern Hemisphere Weather
Maps are reasonably accurate to about 10°N., giving ample
area below 29°N in which to measure trades. No great need
was felt to measure all of the trades area lest some impor-
tant fluctuations be missed. As for the westerlies, how-
ever, while the maps were deemed accurate up to at least
60°N., it was felt that many fluctuations north of 45°N
might have little or no relation to the current in the main
gyral of the Gulf Stream System. The wind data used here
were determined with the template shown in Figure 1. The
twenty pairs of points were placed along the periphery of
the Bermuda-Azores high of the Normal Annual Map. The break
between the trades and westerlies sections of the template
off the southeast coast of the United States corresponds to
an area of slack gradient on the map. Seen in retrospect,
the break probably should have been measured in order to
catch the variations in gradient apparent from month to month.
Also in retrospect it would have been better perhaps if the
central part of the westerlies template had been located in
a somewhat higher latitude in order to avoid its crossing
through the center of the Bermuda-Azores high on some of the
latter's short-period northward excursions.

Long-Time Monthly Averages

"Normal" template trades. In a previous study (Chase,
1951), the center pressure of the Bermuda-Azores high was
compared to surface current velocities in a section of the
trade wind belt. (Fuglister (1951) showed a good correlation
between trade winds and currents). It was claimed that the
center pressure was some measure of the strength of the trades.
When we plot the template measured "normal" trades along with
the center pressure and surface current data (Fig. 2), we see
that the correlations are good between the three sets of data.

FIGURE 1

Center pressure Bermuda-Azores high

Current speeds in the Trades

———— observed
– – – – harmonic analysis

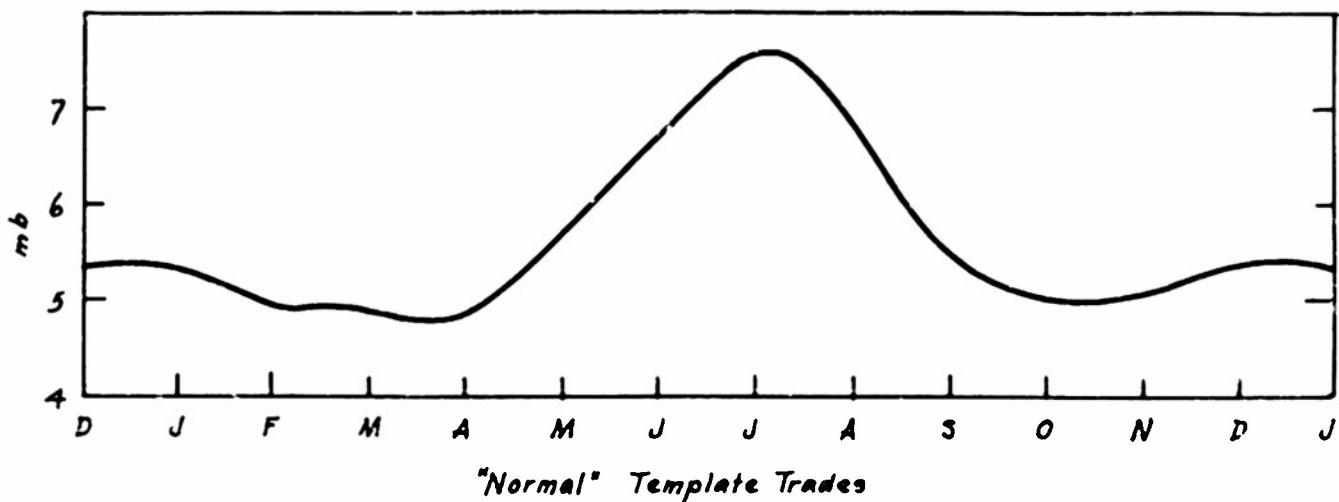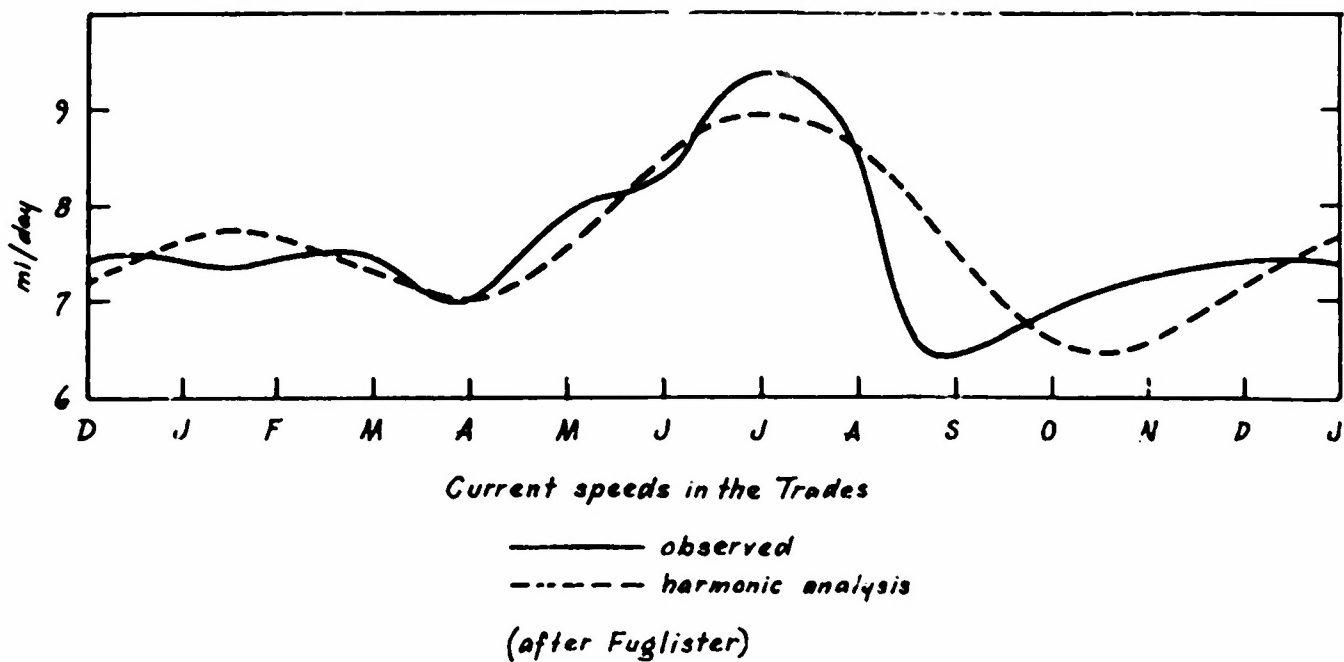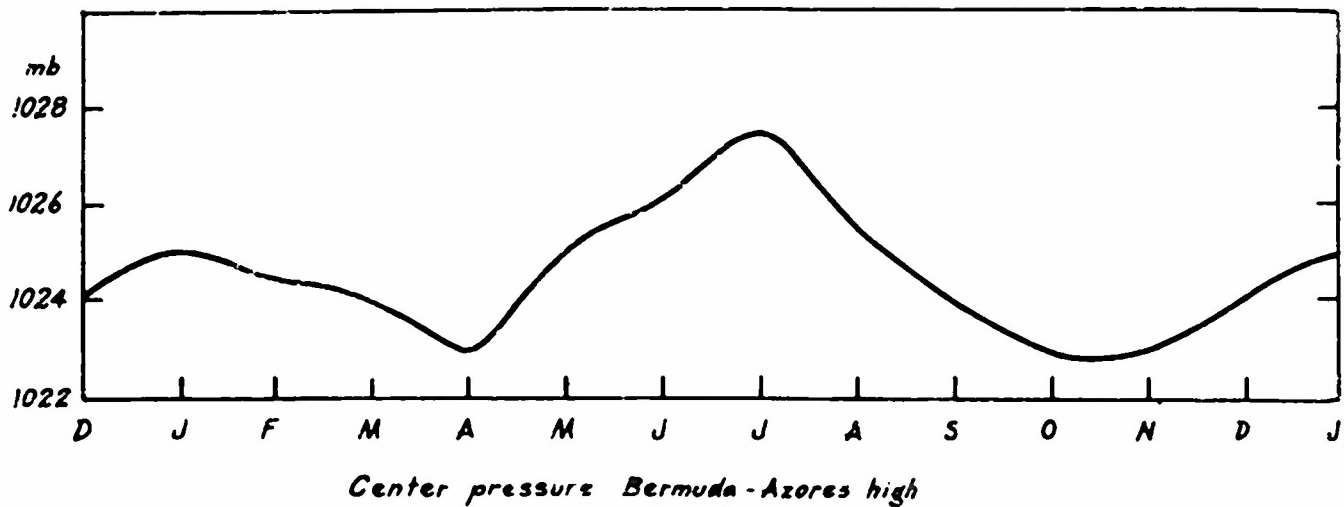(after Fuglister)

"Normal" Template Trades

FIGURE 2

This substantiates the claim, serves as a check on the template method and agrees with the theory of wind-driven currents. The outstanding feature of the trades curve is the July maximum. Slight fall and spring minima and a winter maximum are present, but by and large the graph is flat from October through April.

"Normal" template westerlies. The curve for the westerlies (Fig. 3) as determined from the template has a distinct "W" shape. It shows maxima in January and July and minima in April and September, the primaries being January and September. The lesser similarity of this curve to the trades currents curve appears to favor those theorists who believe that the trades alone are the prime mover of the current system.

Currents off the southeast coast of the U. S. Fuglister calculated a curve for the annual variation in surface currents for an area in the Stream south of Hatteras. This is shown in Fig. 4a. In its main features it is somewhat similar to the trades current curve. It has a large summer maximum and a slight winter maximum. The minima are in February and November as compared to the trades minima in April and September. The velocities are, of course, much larger in the Stream than in the trades.

The next curve (Fig. 4b) is for the northbound component of surface current for a large area extending from the coast to the longitude of Bermuda. Thus, it represents current at approximately right angles to the Bermuda-Charleston line. The curve is remarkably similar to the Fuglister trades curve and is further evidence for the "trades-alone" theory. The monthly values for the northbound component of current are about two miles per day less than those for the trades.

Trades plus westerlies. The next curve (Fig. 5a) results from the addition of the trades and westerlies curves shown above. It retains the "W" shape of the westerlies but now the winter maximum is less pronounced. In comparison with the trades currents and the northbound components its values are too high in winter. As was mentioned above, it is possible that a change in the location of the westerlies section of the template would result in a better coverage of the "effective" area. Some experimentation along this line gave a trades plus westerlies curve which was closer to the current curves. It was felt, however, that the time is not yet ripe in terms of our knowledge of the Gulf Stream to pursue this line further.

Slope of sea level, Bermuda minus Charleston. The mean monthly slope of sea level as given by the tide gauges at Bermuda and Charleston is shown in Figure 5b. The curve is remarkably similar to that for trades plus westerlies.
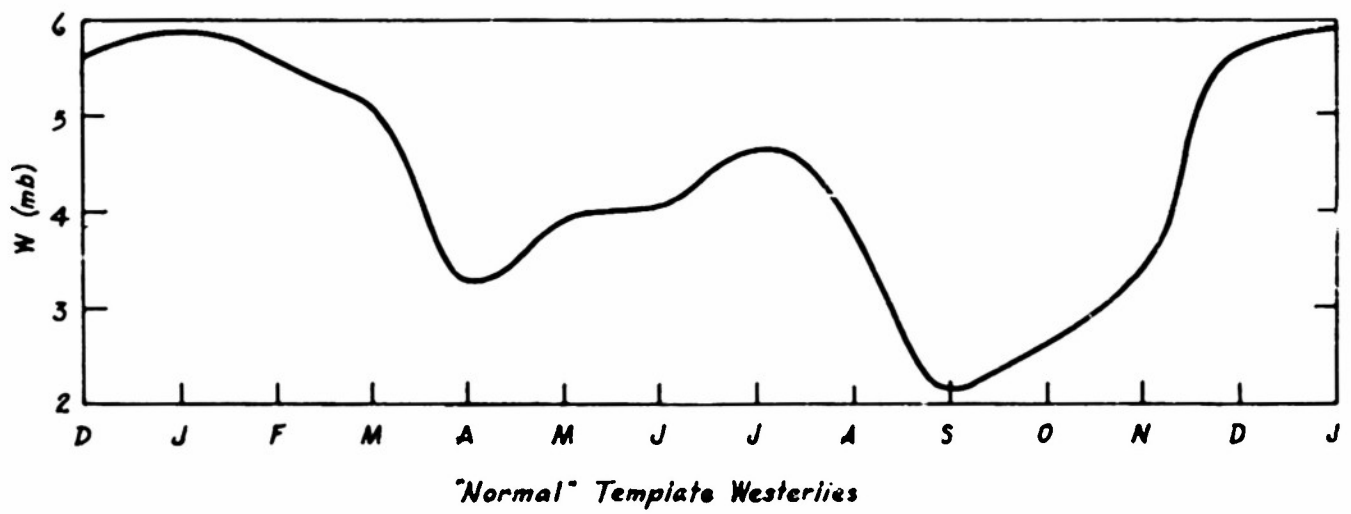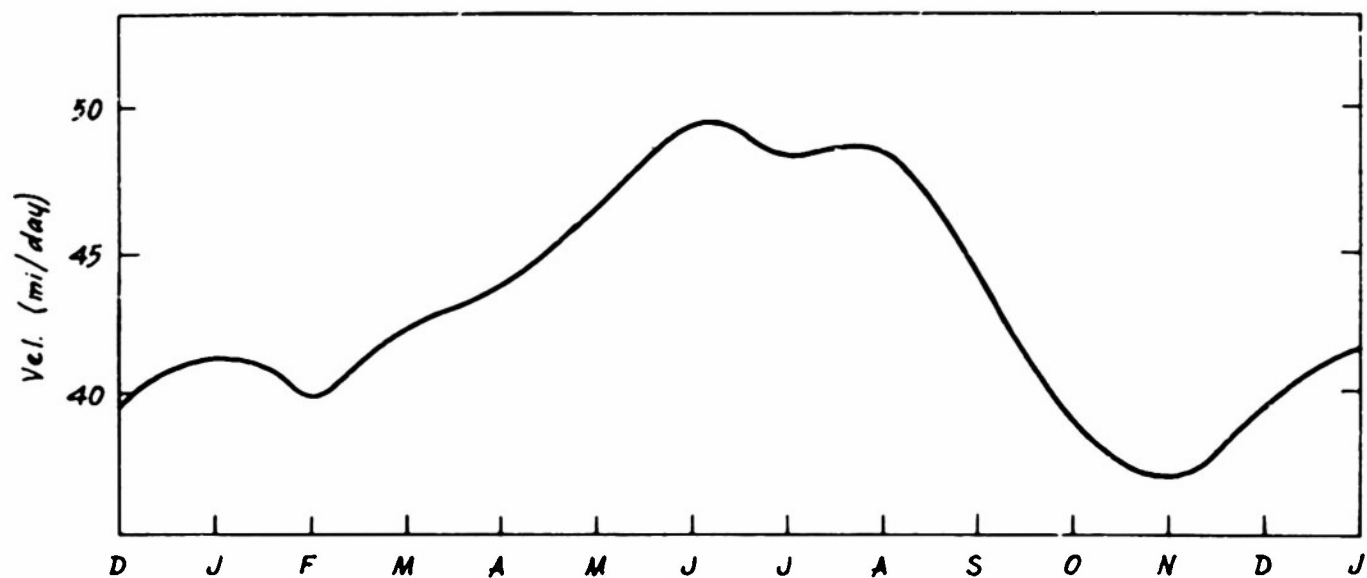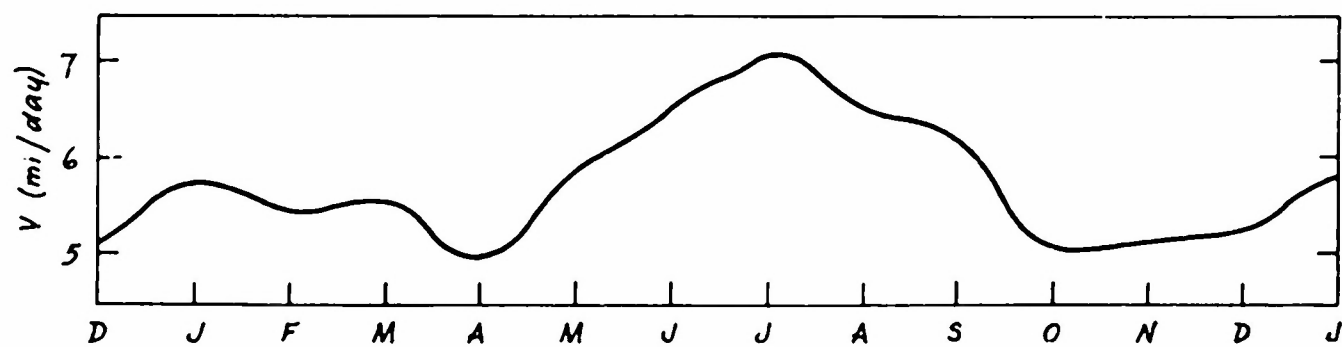
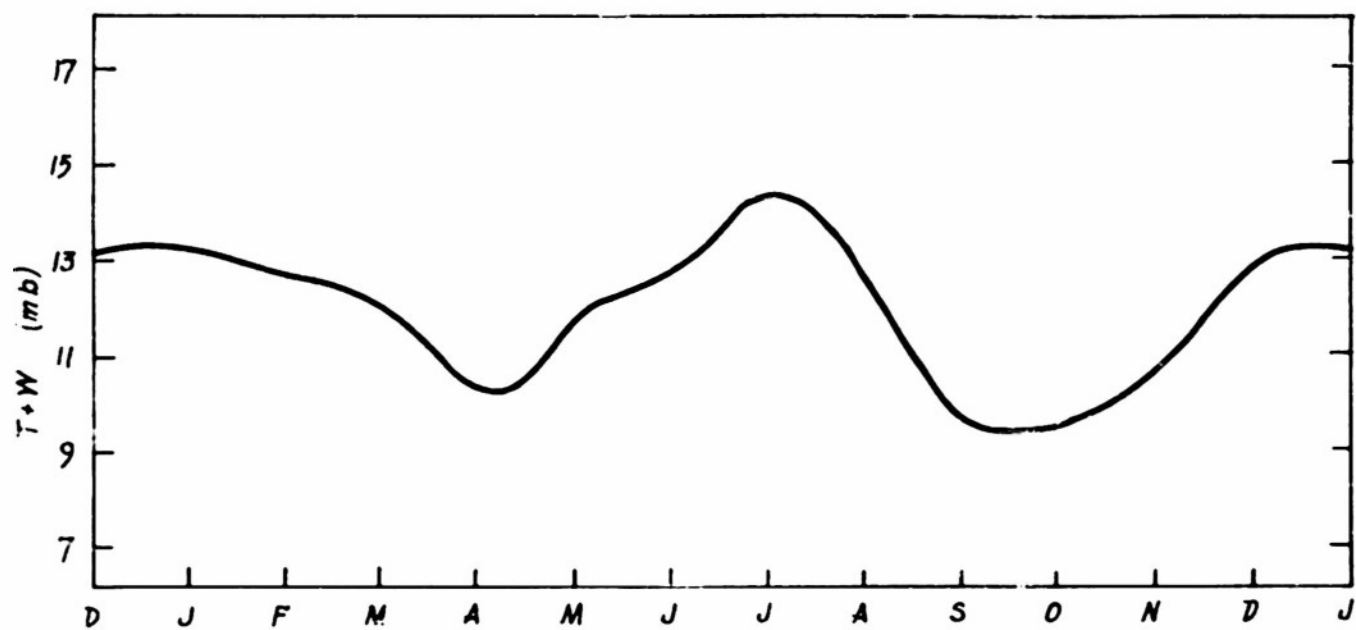"Normal" Template Westerlies

FIGURE 3

a. Velocity of surface currents south of HATTERAS.
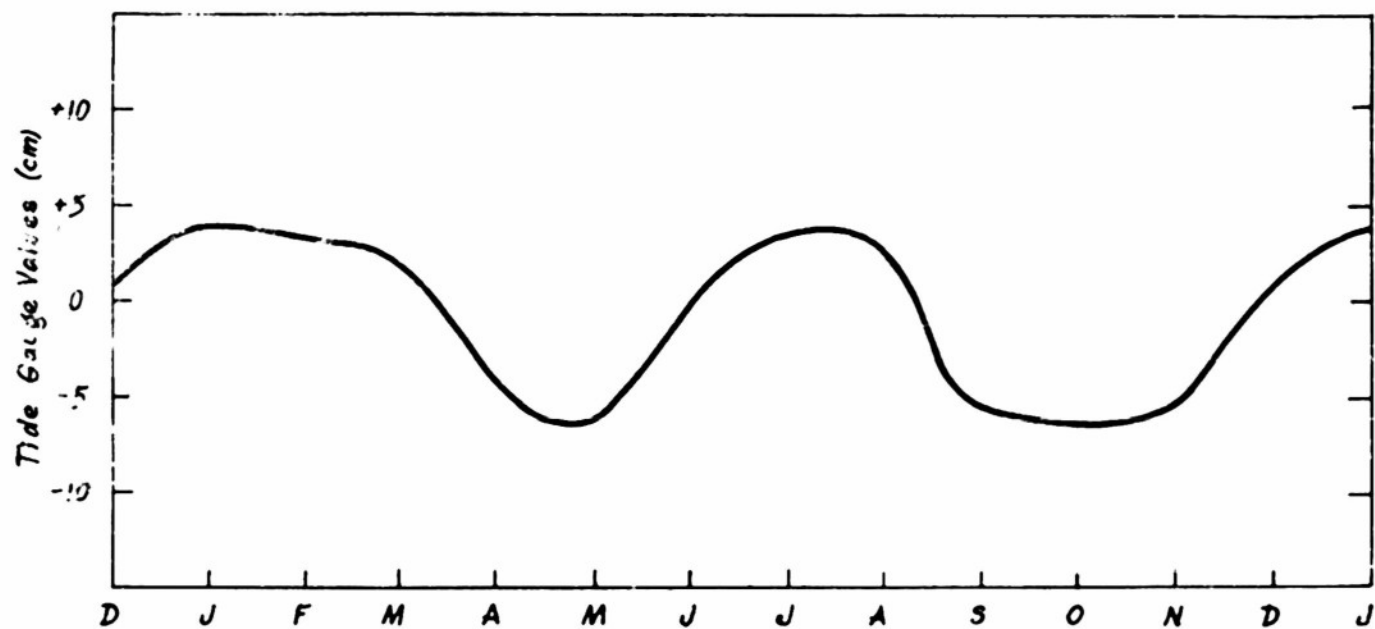(after Fuglister.)

b. Northbound components of surface currents - 29°-33° N. Lat.

FIGURE 4a & b

a. T+W   Trades plus Westeries

b. B-C Slope of sea level BERMUDA - CHARLESTON

FIGURE 5a & b

Similarly, its winter values are too high for the current values. Winter is the season when Charleston has the greatest number of offshore winds. Just how much these winds lower sea level at Charleston is beyond the scope of this paper, but a qualitative indication is given in the next two graphs. They are Figure 5c, the percentage frequency of net offshore winds at Charleston 1931-1938, and Figure 5d, the offshore stress in the Charleston area calculated from a report by Cochran and Osborn (1950). Both indicate that if an allowance for the effects of these winds could be applied to the Charleston values, the resulting Bermuda minus Charleston curve would be more similar to the current curves.

Height of sea level at Galveston. The graph of mean monthly heights of sea level at Galveston (Fig. 5e) was plotted with the negative values above and the positive values below the arbitrary zero, since Galveston is on the left side of the Stream. In view of the fact that Galveston is so far from the Stream, it is perhaps surprising how much its curve resembles those for Bermuda minus Charleston and trades plus westerlies. It does have a larger amplitude and a slightly later spring trough and summer peak than the other two curves, but otherwise follows them closely. As with Charleston, offshore winds are more frequent in winter at Galveston and it is similarly possible that proper allowance for these winds would make the Galveston curve more like the current curves.

Height of sea level at Miami. The graph of mean monthly heights of sea level at Miami is shown in Figure 5f. It is in good agreement with the three preceding ones except for the section March through June. Compared with the trades currents and the northbound components, sea level is too low at Miami from December through April. The contribution of wind to this discrepancy is not as obvious as in the cases of Charleston and Galveston. Miami, being on a peninsular, is perhaps less affected as to height of sea level by on- and offshore winds. There is, however, some indication in the U. S. W. B. Climatic Atlas of the Oceans (1938) of a weaker onshore stress in winter and spring.

Extraneous Variables

Early in the study, comparisons were made of shorter period averages of trades plus westerlies, the Bermuda minus Charleston data, and sea level height at Galveston. It was found that the agreement was poor in month-to-month averages, only slightly better in two-year mean monthly averages, and became good only when three or four years were averaged together for the mean monthly values. A check was made to assure that these results
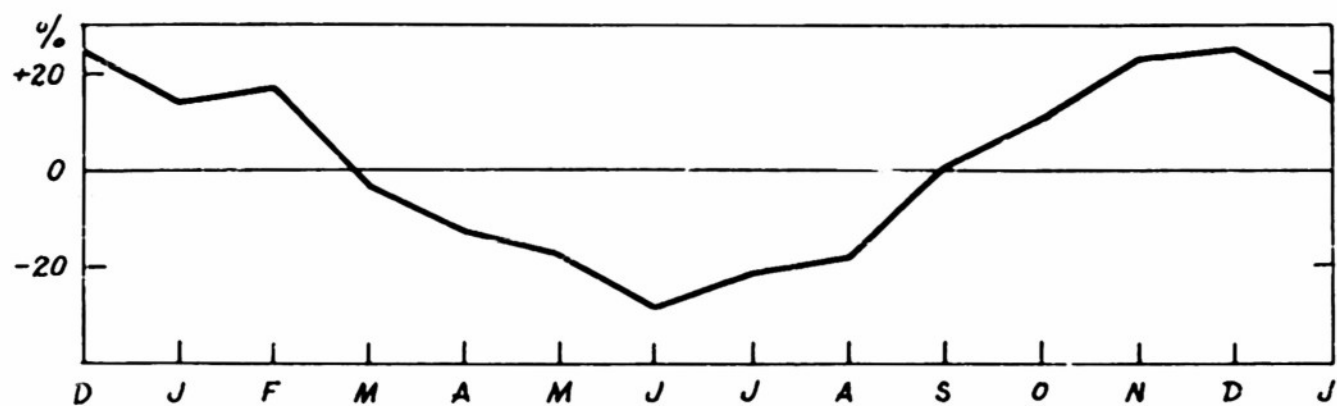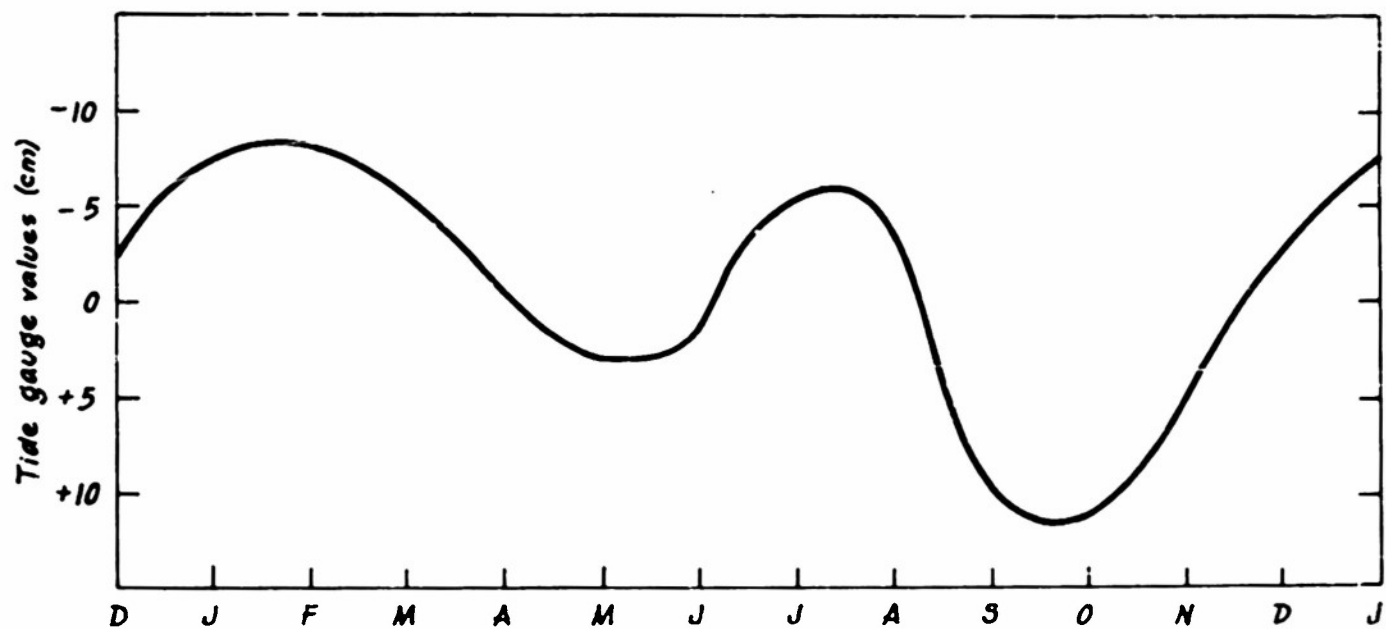
c. Percentage frequency of net offshore winds
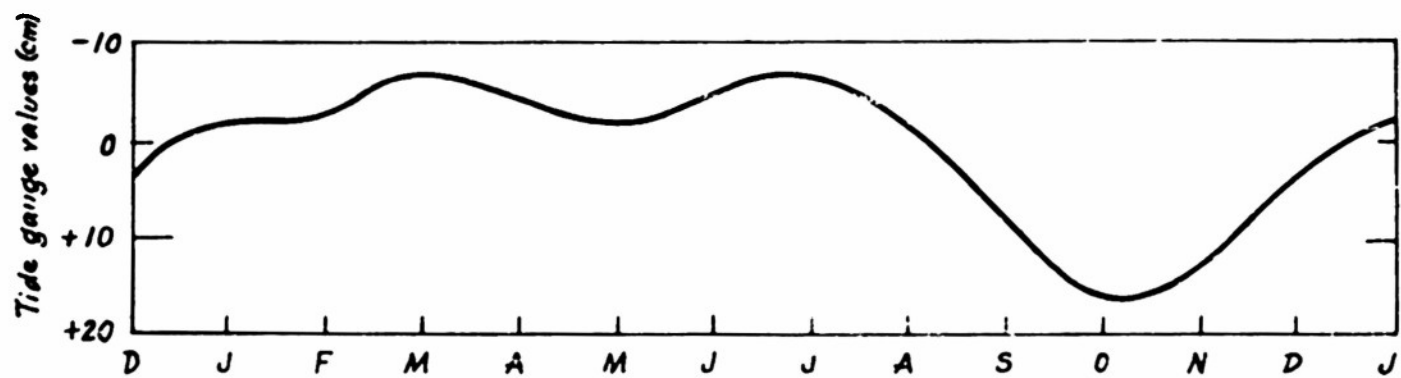   at CHARLESTON 1931-1938.
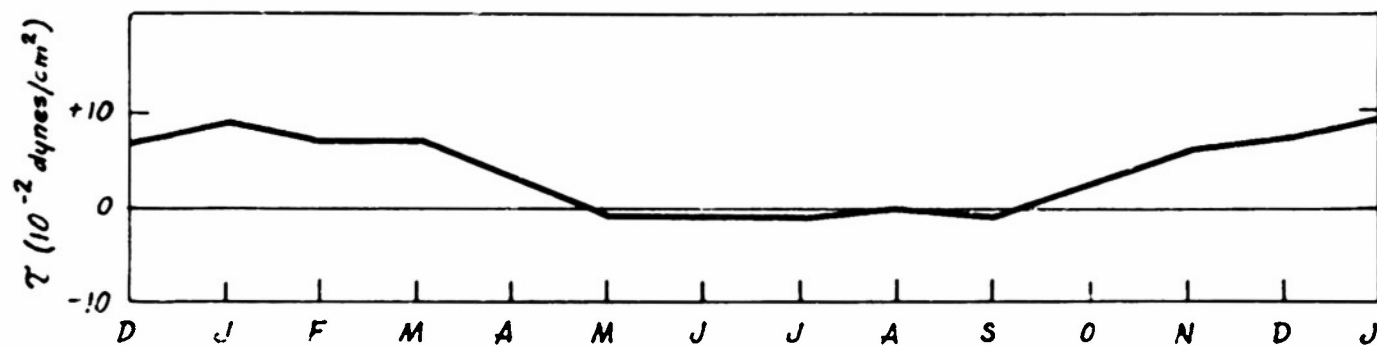
d. Offshore stress CHARLESTON area.

FIGURE 5c & d

e. Height of sea level at GALVESTON

f. Height of sea level at MIAMI

FIGURE 5e & f

were not due simply to a one- or two-year lag in any of the
curves. It appears, then, that the lack of agreement in the
one- and two-year averages must be due to the anomalous
influence of extraneous variables and that the anomalies
average to nil in the longer period averages. The following
may be such variables:

    a. The effects of water from the South Atlantic and
       from the coastal waters to the north of the Stream;

    b. The effects of local wind stresses on the tide gauge
       readings;

    c. Temporary time lags;

    d. The location of pressure centers relative to the
       template.

And of lesser importance:

    e. The ratio of geostrophic wind to sea level stress;

    f. The effects of current below the wind-driven layer;

    g. Rainfall and runoff in the vicinity of the tide gauges.

Special studies will be required on each of these variables
to determine the amount of their influence. Meanwhile, the
direction of their influence can easily be spotted for some of
the variables. It is easy, for example, with the weather maps,
to measure the offshore component of geostrophic wind near a
tide gauge or to spot cases where the template crosses a pres-
sure center. On the other hand, continuous data on the amount
of water entering the Gulf Stream System from the South Atlantic
Ocean are nonexistent.

Short-Time Monthly Averages

In order to average out some of the anomalous effects of
extraneous variables and yet maintain some semblance of chrono-
logy, the short-period figures given here, except for those of
transport, are three-month running averages.

The first graph is for trades plus westerlies (Fig. 6a).
The dashed sections result from the deletion of the values for
certain months in which it appeared that anomalous pressure
distributions gave unrepresentative template readings. These
dashed sections were made by way of experiment only and the
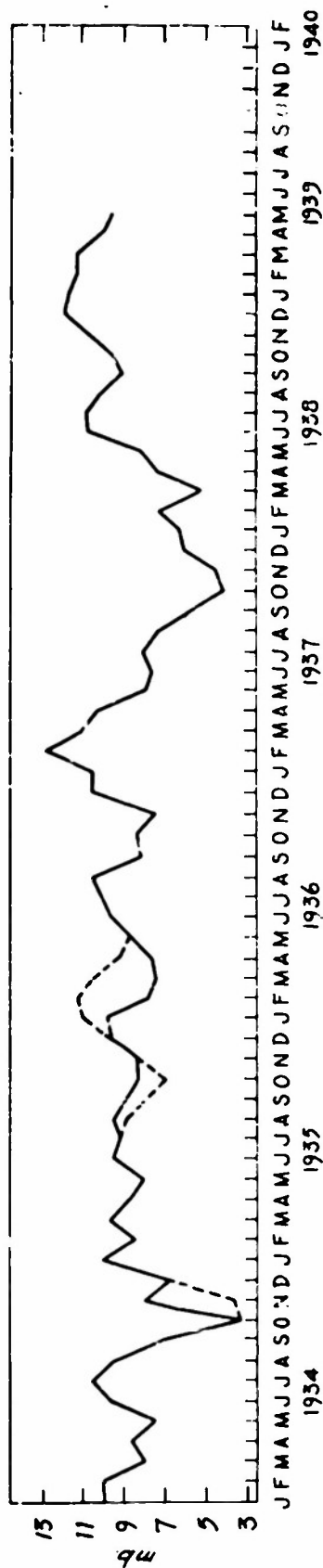
a Template trades plus westerlies – three month means
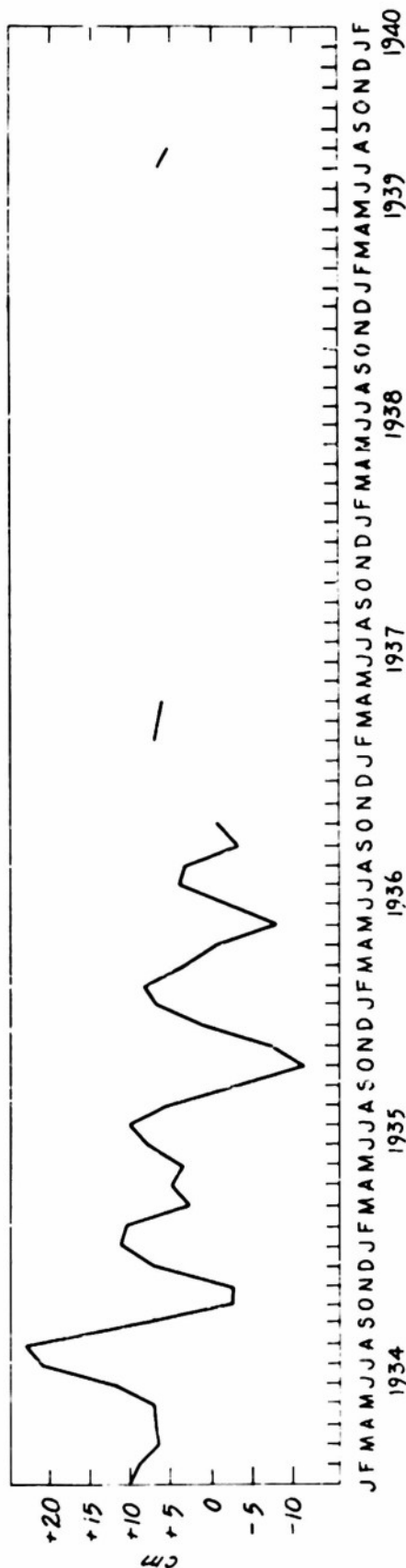
b Relative slope of sea level between Bermuda and Charleston – three month means
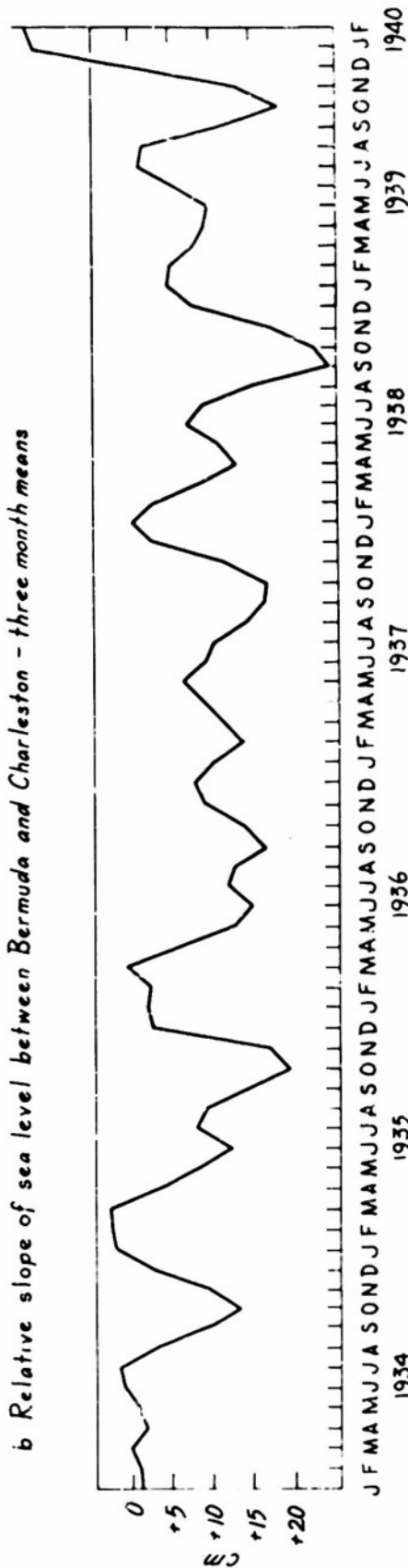
c Heights of sea level at Galveston – three month means.

FIGURE 6a & b & c

experiment was confined to only a small percentage of the maps measured.

In Figures 6b and 6c are the graphs of the Bermuda minus Charleston, and Galveston tide gauge values. Both are in terms of departures from an arbitrary constant. With some exceptions the three curves follow parallel paths.

The Miami gauge curve (Fig. 6d), as might be expected from the long-time averages, fits the other curves best from late summer through early winter.

In Figure 6e are the Iselin transport values. The dashed sections of the curve were interpolated by Iselin. He has already compared the curve to the month-to-month values of the Miami gauge so it is not surprising that it also agrees well with the three-month running Miami values. There is also fairly good agreement with the Galveston and trades plus westerlies curves. The troughs and peaks of the transport curve lag one to three months behind those of the other two curves except for the trough in the fall of 1939. Just how much the fluctuations in the deeper currents may follow those of the surface is not known but it is generally supposed that some lag does exist. It is unfortunate that the wind data end in the summer of 1939 and that there are so few Bermuda gauge values available for the period of the transport data.

The last curve (Fig. 6d) is for the trades. It is in poorer agreement with the interpolated sections of the transport curve than is the trades plus westerlies curve but follows the observed values about as well. The peak of late August 1938 in the observed transport data corresponds to the July peak in the trades.

Conclusions

1. Values for the trade winds, measured with a geostrophic template from mean weather maps, agree well with surface current data for an area in the trades zone and for an area off the southeast coast of the United States, in long-time monthly averages. In short-time averages, the comparison between the trades and the best available transport data shows only fair agreement.

2. Template values for trades plus westerlies agree rather well in both long-time and three-month means with:

    a. tide gauge readings at Bermuda minus those at Charleston;
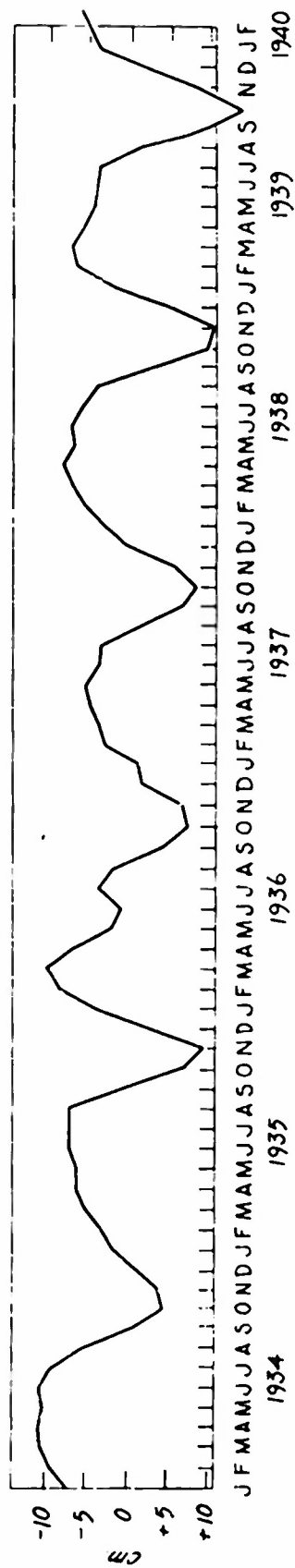
d Heights of sea level at Miami - three month means
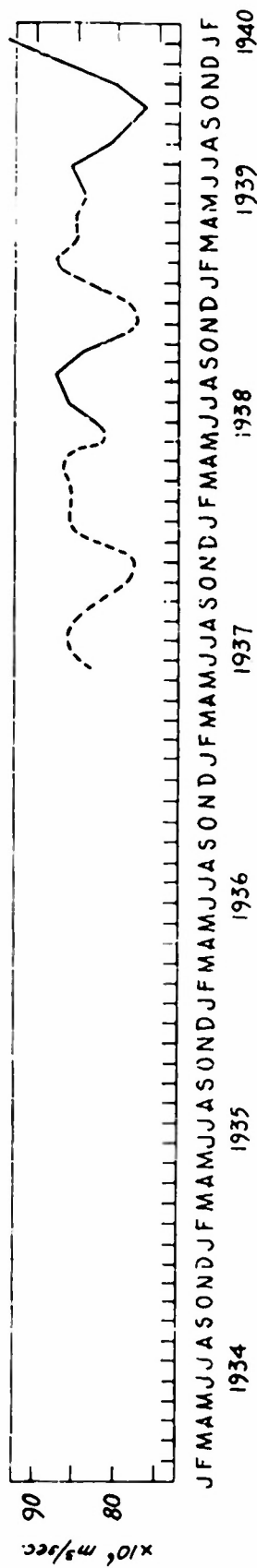
e Gulf Stream transport (after Iselin)
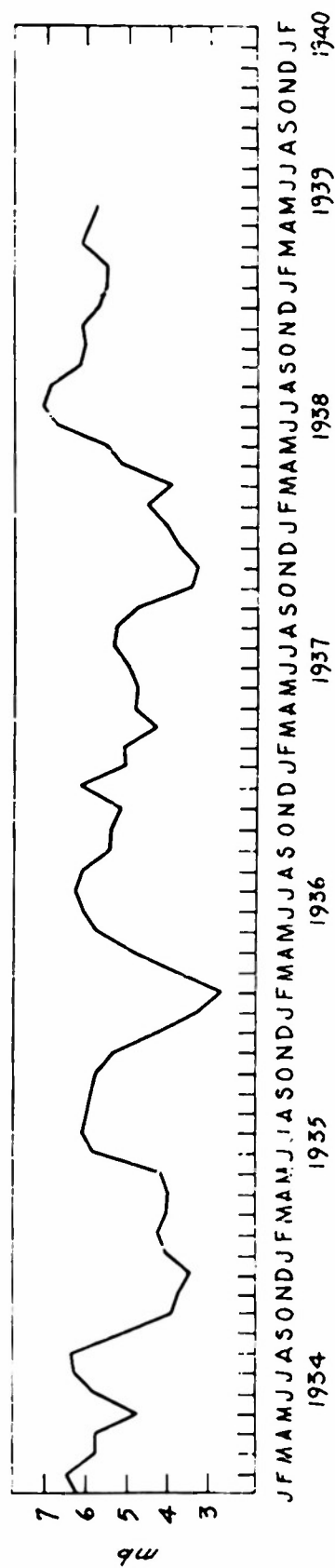
f Template trades - three month means.

FIGURE 6d & e & f

b.   tide gauge readings at Galveston;

and

c.   the late summer through early winter readings for the Miami tide gauge.

3.   There appears to be a strong possibility for improvement in the agreements of 2, above, and for extension of them to even shorter time periods when more is known about the influence of certain extraneous variables and appropriate adjustments made therefor.

4.   As a consequence of the geostrophic equation and of the theory of wind-driven currents, one might suppose that the gauge and wind data of 2, above, would agree with the flow in the Gulf Stream and adjacent waters. While some agreement was found in both long- and short-period averages, better agreement appears likely when the adjustments mentioned in 3, above, can be applied.

5.   The peaks and troughs of the transport curve often lag one to three months behind those of the tide gauge and wind curves. This lag may correspond to that between surface currents and those below the wind-driven layer.

6.   The trades agree with the transport about as well as do the trades plus westerlies, except where the transport is interpolated. Thus, no conclusion can be stated in favor of either the "trades alone" group of the "trades plus westerlies" group of the wind-driven theorists.

7.   A long step in the progress on deciding between trades alone and trades plus westerlies will be made when a long series of continuous data for the Gulf Stream is available.

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